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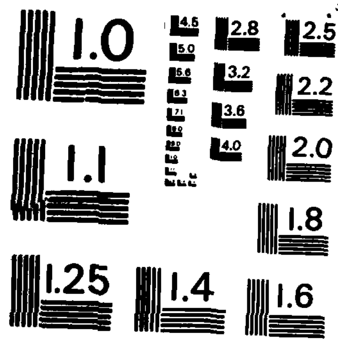

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NRL Memorandum Report 5765

Gamble-II Imploding Sodium Plasma

I. Calibration of the Heliumlike Resonance Line as a Pump Source and Detection of Fluorescence in Neon

J. DAVIS, J. E. ROGERSON AND J. P. APRUZESE

Plasma Radiation Branch
Plasma Physics Division

April 10, 1986

This research was sponsored by the Defense Nuclear Agency under Subtask QIEQMXLA, work unit 00006 and work unit title "XRL Source."

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Numerical simulations are performed describing the behavior and properties of an imploding cylindrical annular sodium plasma. Special attention is devoted toward calibrating the power radiated in the heliumlike resonance line for application as a pump source in x-ray laser experiments. Detection of fluorescence in a nearby neon plasma is also discussed. Keywords:

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GAMBLE-II IMPLODING SODIUM PLASMA
I. CALIBRATION OF THE HELIUMLIKE RESONANCE LINE AS A PUMP SOURCE AND DETECTION OF FLUORESCENCE IN NEON

I. Introduction

A variety of schemes have been proposed suggesting ways of creating a population inversion and gain coefficients in excess of unity in the x-ray region. One attractive scheme involves the flashlamp concept where the radiated flux from one plasma pumps another plasma to create conditions favorable to the emission of coherent radiation. Of the many photopumped schemes based on line coincidence, the Na-Ne scheme is particularly interesting because the lines match to two parts in 10^4 at a wavelength of 11Å. In particular, the NaX $1s^2\ {}^1S_0$-$1s2p\,{}^1P_1$ line at 11.0027Å pumps the NeIX $1s^2\ {}^1S_0$-$1s4p\,{}^1P_1$ line at 11.0003Å. The strongest lasing lines in the pumped neon system are the $2p\,{}^1P_1$-$3d\,{}^1D_2$, $2p\,{}^1P_1$-$4d\,{}^1D_2$, and $3d\,{}^1D_2$-$4f\,{}^1F_3$. This scheme is particularly interesting because: (1) both ions are heliumlike - a closed shell configuration exists over a large parameter space of temperature and density, (2) the line coincidence is almost perfect - two parts in 10^4 - which is about a Doppler width, and (3) both ions can be produced easily in the laboratory by Z-pinch plasmas driven by pulse power generators and laser plasmas. A comprehensive discussion on the kinetics and the plasma environment required for lasing to occur has been presented in two earlier papers.[1,2] The details of the calculations can be found there. In this paper we will focus on the sodium pump source and determine the feasibility of producing a heliumlike sodium plasma radiating an intense flux in the heliumlike resonance line by means of a current driven gas puff implosion.

The treatment presented here is based on the implosion dynamics of a cylindrical annular gas puff plasma consisting initially of sodium vapor. The implosion is driven by a high current discharge typical of the GAMBLE

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II pulse power generator. The theory describing the implosion is based on a dynamic pinch model self-consistently coupled to a non-LTE ionization dynamic and radiation transport model.[3] The radiation transport employs a probability of escape method. This provides a self-consistent picture of the temperature, density, size, and level population during the plasmas' evolution. Such an simplified approach ignores any pathological behavior such as instabilities sometimes exhibited by these imploding plasmas. However, the approach adopted here does provide a good starting point for determining the feasibility of producing the radiation flux in the heliumlike resonance line required to pump the $1s^2$-$1s4p$ level of heliumlike neon leading to a population inversion and gain coefficients in excess of $1 cm^{-1}$.

II. Results and Discussion

The non-LTE dynamic pinch model has been discussed in considerable detail elsewhere. The reader is referred to Ref. 3 for further particulars. The collisional-radiative model for sodium consists of ground states for all the ionization stages and contains structure up to principal quantum number n=5 in the lithium-, helium-, and hydrogen-like ionization stages. The n=4 and 5 levels have been averaged and are represented as single levels.

For illustrative purposes, the results of numerical simulations are presented for 30μgm/cm of sodium uniformly distributed between the initial inner and outer radii of 0.95 and 1.55 cm, respectively and 4 cm in length. The driving current waveform typical of the GAMBLE II generator is shown in Fig. 1. The current reaches a peak value of 1.25 megamp in about 70 nsec and then decays to about 0.45 megamp in about 50 nsec. The remainder of the current waveform, i.e., beyond about 120 nsec, is for computational expediency. The temporal behavior of the inner (A) and outer (B) radius is shown in Fig. 2. The inner radius collapses and stagnates on axis while the outer radius continues inward until the fluid pressure retards the forward runin motion and the plasma bounces. The final pinch radius is about 1/10 the initial outer radius. The variation of velocity with time is shown in Fig. 3, attaining a peak value of 23 cm/μsec at about

120 nsec which is well after peak current. This behavior is characteristic of the GAMBLE II current driven implosions. The temperature and density time histories are shown in Figs. 4 and 5, respectively. The temperature profile peaks at about 380 eV while the density profile peaks at $2x10^{19}$ ions/cm^3, both profiles maximizing around 140 nsec. These values are similar to those obtained for neon[4] which is not too surprising since sodium is just one atomic number away from neon. The total radiative yield as a function of time is shown in Fig. 6 and is about 4.7 kilojoules. The power radiated (in Watts) is presented as a function of time (nsec) in Fig. 7 for radiation in energy bins labelled K- and L-lines. The K-lines refer to radiation originating from transitions equal to or above 1 KeV and L-lines representing those transitions below 1 KeV. Within the context of this study the L-lines refer strickly to transitions with energies less than 1 keV emanating from the Li-, He-, and H-like ionization stages only. The L-lines appear first and linger longer than the K-lines but the K-lines reach a peak value greater than the corresponding peak value attained in the L-lines. Also, in the case of argon, the K-lines peak occurs just before the peak in the L-lines.[5] The reasons for this have been discussed in detail elsewhere and need not concern us here.[3] The emission spectrum at 141 nsec is given as a function of energy (KeV) in Fig. 8. The line intensities are fairly well distributed with peaks occurring in the K-shell above 1KeV and in a band of lines around 250 eV. This result, is to some extent, model dependent in the sense that an extended sodium model containing more transitions would provide a richer and possibly modified spectrum than the one presented in Fig. 8. Certainly, the total power radiated would increase with an extended model. Since our primary concern was to theoretically calibrate the flux emitted from the heliumlike resonance line, i.e., the flux in the $1s^2\ {}^1S$-$1s2p\ {}^1P$ transition, we present in Fig. 9 the power radiated in this line as a function of time. At or near the pinch the power radiated is about $8x10^{10}$ watts. This is in very good agreement with the peak value of $5x10^{10}$ watts obtained experimentally with neon on the GAMBLE II facility.[6]

In order to determine the behavior and magnitude of the radiation flux from the He_α-like resonance line for a variety of conditions, numerical simulations were carried out for B = 1.55 cm and A = 0.95 cm (outer and inner radii, respectively) as a function of M/ℓ. These results are

summarized in Fig. 10. Fairly impressive yields can be obtained for the above conditions with a peak value of 0.08 terrawatts when M/ℓ is roughly between 25 and 30 μgm/cm. For higher and lower values of M/ℓ the yield drops precipitously. For higher values of M/ℓ, i.e., higher than, say, 40 μgm/cm, the load becomes too massive to achieve large values of runin velocity and subsequently is inefficient at converting kinetic energy to thermal energy at high temperatures commensurate with the heliumlike ionization stage. On the other hand, for loads of small mass, the conversion of runin kinetic energy to thermal energy causes overheating and burn-through of the heliumlike ionization stage leading to a reduction in the emission from the heliumlike ions, provided, of course, the plasma is thermal.

Similarly, for fixed values of M/ℓ=30μgm/cm and B=1.55 cm, results were obtained for the power radiated in the heliumlike resonance line by varying the inner radius. These results are displayed in Fig. 11 as a function of ΔR, the difference between the outer and inner radius. The total power radiated in the He_α-like resonance line over the range of values considered is relatively insensitive to ΔR, having a value of 0.08 terrawatts at ΔR=0.15 cm and falling to 0.07 terrawatts at ΔR=0.50 cm, primarily because for the value of M/ℓ=30μgm/cm, the load is efficiently coupled to the generator in terms of generating K-shell radiation.

From these calculations it is apparent that if it is experimentally feasible to implode a cylindrical annular sodium plasma under the right set of conditions, then it is theoretically possible to attain a reasonably potent pump source from the heliumlike resonance line of the order of 0.08 terrawatts at 11.0027Å. The question confronting us now is whether this pump source is adequate to pump the heliumlike neon $1s^2\ {}^1S$-$1s4p\,{}^1P$ transition and create a population inversion in the upper state that may subsequently lead to gain coefficients in excess of unity. To answer this question we assume a neon plasma to be 1 cm away from the sodium pump source. The area of a cylinder centered on the pump 1 cm away from the pump is 25.1 cm^2. Also, the line width of the $1s^2\ {}^1S$-$1s2p\,{}^1P$ line is about $3 \times 10^{14} H_z$, hence, the pump flux is

$$\text{Pump Flux} = \frac{8\times10^{10}\text{watts} \cdot 10^{7}\text{erg/joule}}{(3\times10^{14}\text{Hz})\ (25.1\text{cm}^2)}$$

$$= 10^2 \frac{\text{ergs}}{\text{cm}^2\text{-sec-Hz}}$$

This is roughly the equivalent of a 125 eV blackbody source. From our earlier calculations this would lead to a gain of unity in a cool neon plasma just ionized to the heliumlike stage at 1 cm from the sodium plasma. Even if the neon cannot be placed at a distance of 1 cm from the sodium, fluorescence of the neon would easily be detectable and would represent a major step forward.

To further explore detection of fluorescence in heliumlike neon pumped by heliumlike sodium in Gamble II, assume that a cool (65-100 eV), low-density ($N_I \lesssim 10^{18}\text{cm}^{-3}$) neon plasma, barely ionized to the heliumlike stage, can be placed within 2 cm or so of the sodium pinch pump in Gamble-II. The kinetics of the levels of such a heliumlike neon plasma would be dominated by the sodium pump radiation to the $1s4p\,^1P$ level and resulting cascade of radiative decays. In this case, a simple model can yield reasonable estimates of what the flourescence-induced heliumlike neon resonance line ratios would be.

LEVEL MODEL

1 = $1s^2\ ^1S_0$ ground state in heliumlike neon

2 = $1s2p\,^1P$

3 = $1s3\ell$ singlets

4 = $1s4\ell$ singlets

Definitions

P = pump rate of heliumlike neon $1s4\ell$ singlet level by sodium (sec^{-1}), per ground state ion

A_{43}, A_{42}, A_{41}, A_{32}, A_{31}, A_{21}, = spontaneous decay rates for the indicated transitions (Einstein A's), in sec^{-1}

f_1 = ground state fraction

(f_2, f_3, f_4) = excited state fractions

Equations for Steady State

CREATION RATE	=	DESTRUCTION RATE
Level 4: $f_1 P$	=	$f_4(A_{43}+A_{42}+A_{41})$
Level 3: $f_4 A_{43}$	=	$f_3(A_{32}+A_{31})$
Level 2: $f_4 A_{42}+f_3 A_{32}$	=	$f_2(A_{21})$

Decay Rates

$A_{42} = 4.6\times10^{10}\ \sec^{-1}$, $A_{43} = 6.0\times10^{10}\ \sec^{-1}$, $A_{41} = 1.9\times10^{11}\ \sec^{-1}$
$A_{32} = 2.6\times10^{11}\ \sec^{-1}$, $A_{31} = 8.3\times10^{11}\ \sec^{-1}$, $A_{21} = 8.9\times10^{12}\ \sec^{-1}$

Simple Algebra Yields:

$$f_4/f_1 = 3.38\times10^{-12}P$$
$$f_3/f_1 = 1.86\times10^{-13}P$$
$$f_2/f_1 = 2.29\times10^{-14}P$$

Therefore

f_4, f_3, f_2 are in the ratio 1.0 : 0.055 : 0.00678.

The line intensities (optically thin) are in the ratio

$$f_4A_{41} : f_3A_{31} : f_2A_{21} = 1.0 : 0.24 : 0.32.$$

Therefore, the 1→4 resonance line will be three times as intense as the principal resonance line at 13.45 Å. In case the 1→4 radiation cannot be experimentally separated from the pumping sodium radiation, the 1→3/1→2 ratio of 0.75 is also far above what would be expected (0.1-0.2) for an isolated neon plasma, and would indicate flourescence and pumping.

ACKNOWLEDGMENTS

This work was supported in part by SDIO, through DNA, and ONR. We would also like to express our thanks to Dr. D. Duston for developing the rate tables and Dr. P. Kepple for making them available. Also, we thank Chris Agritellis for his assistance in making the SIMPLODE code operational on the VAX computer and to Dr. F. C. Young for his comments on the manuscript.

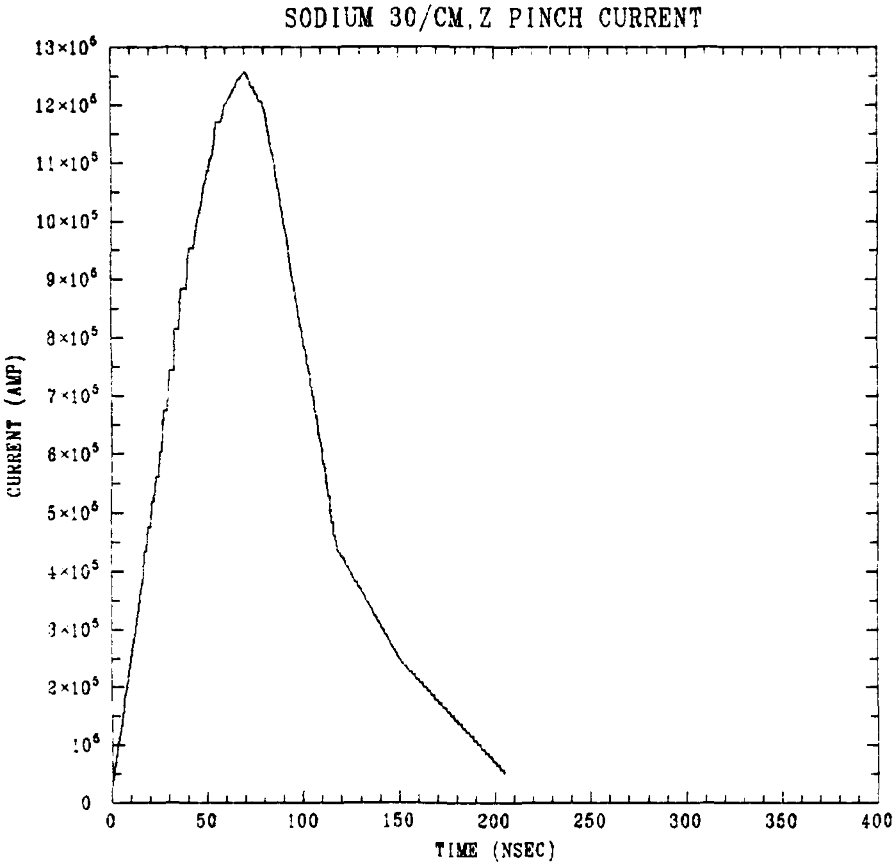

Fig. 1. Current waveform as a function of time.

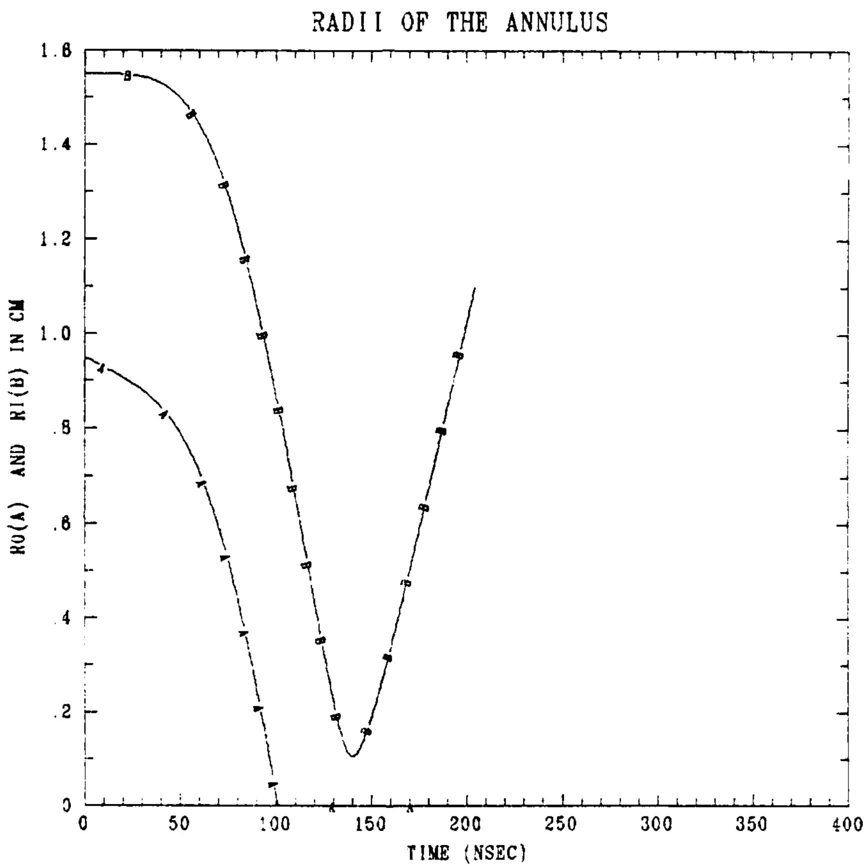

Fig. 2. Radii as a function of time.

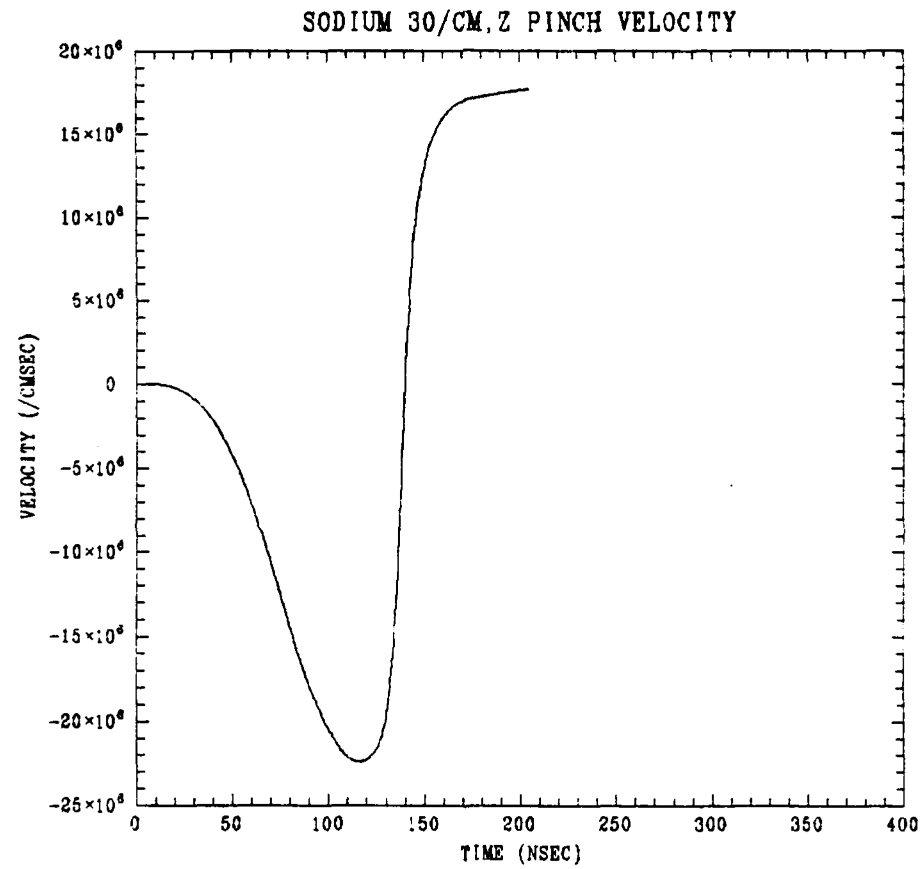

Fig. 3. Velocity as a function of time.

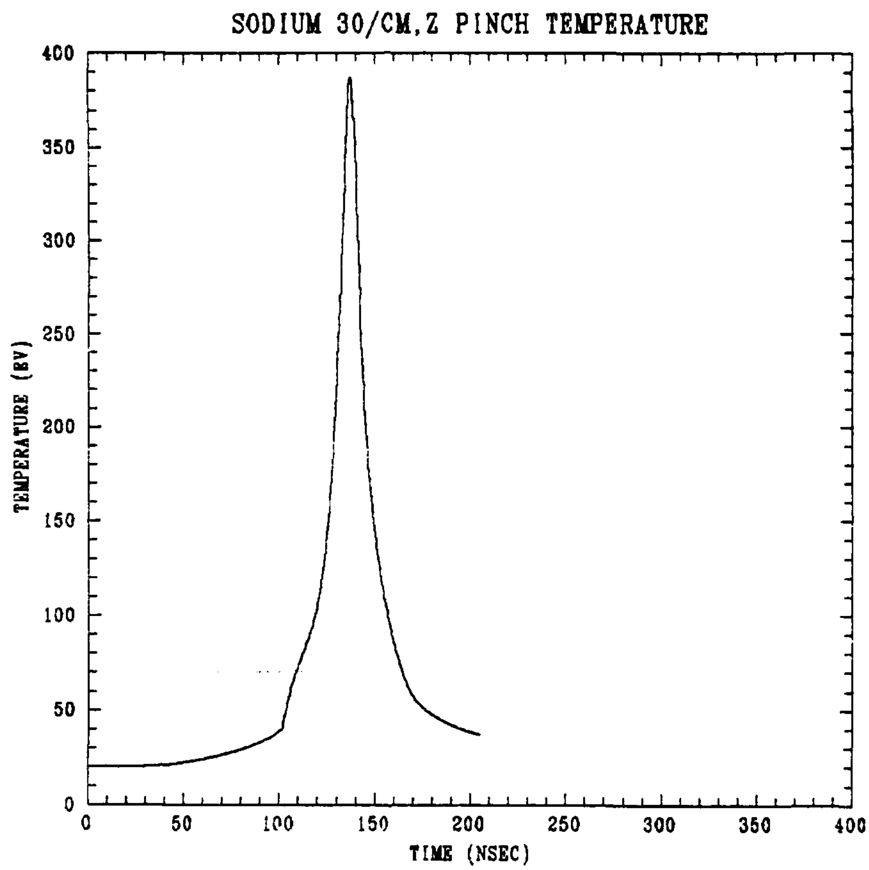

Fig. 4. Temperature as a function of time.

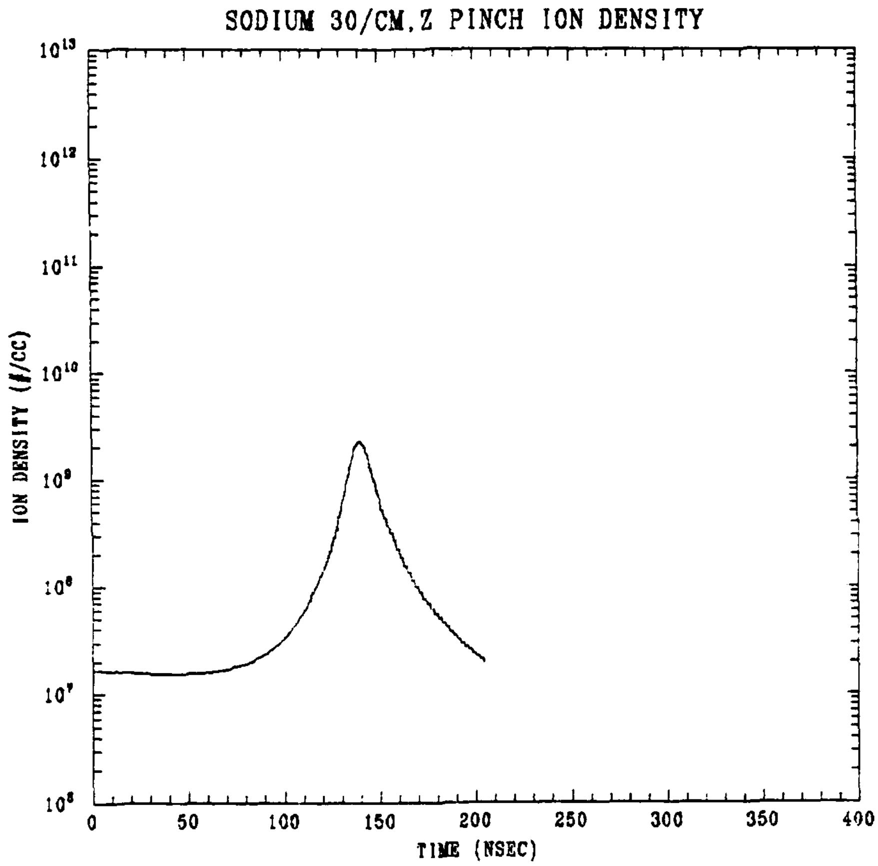

Fig. 5. Ion density, reduced by 10^{10}, as a function of time.

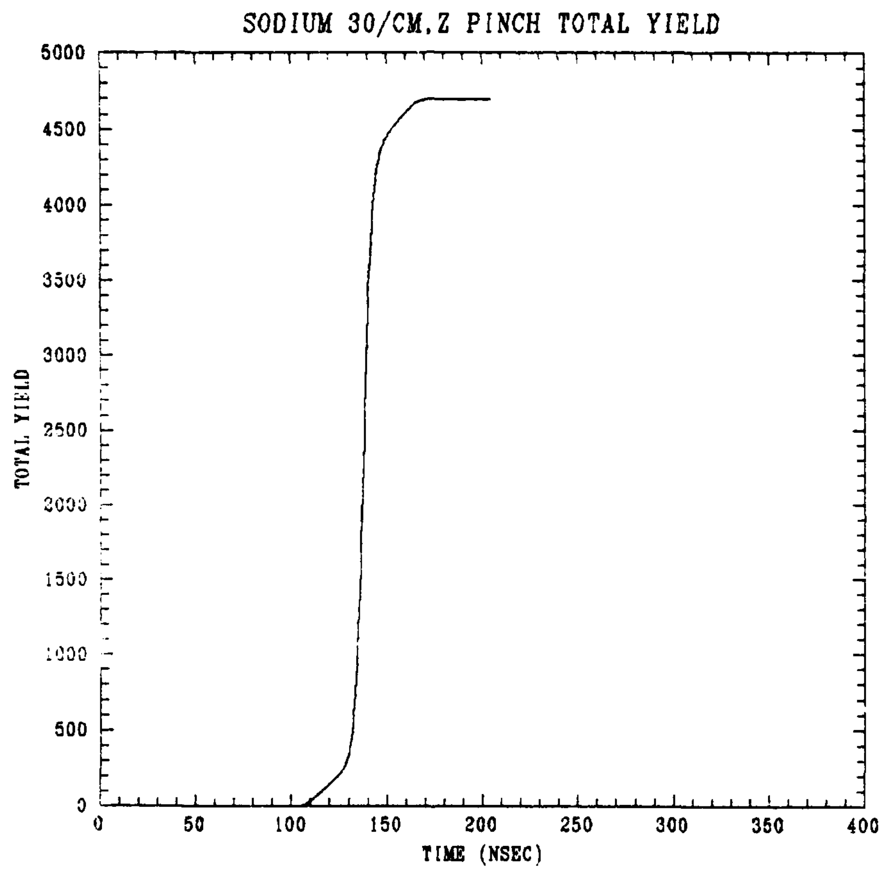

Fig. 6. Total radiative yield as a function of time.

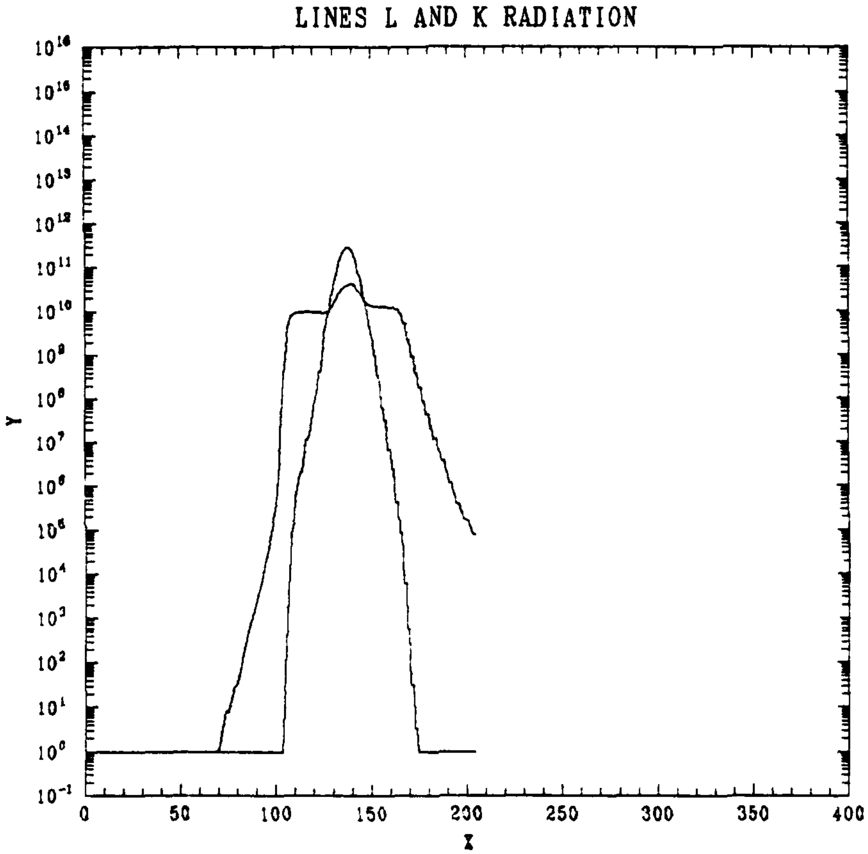

Fig. 7. Power radiated in L-and K-lines as a function of time.

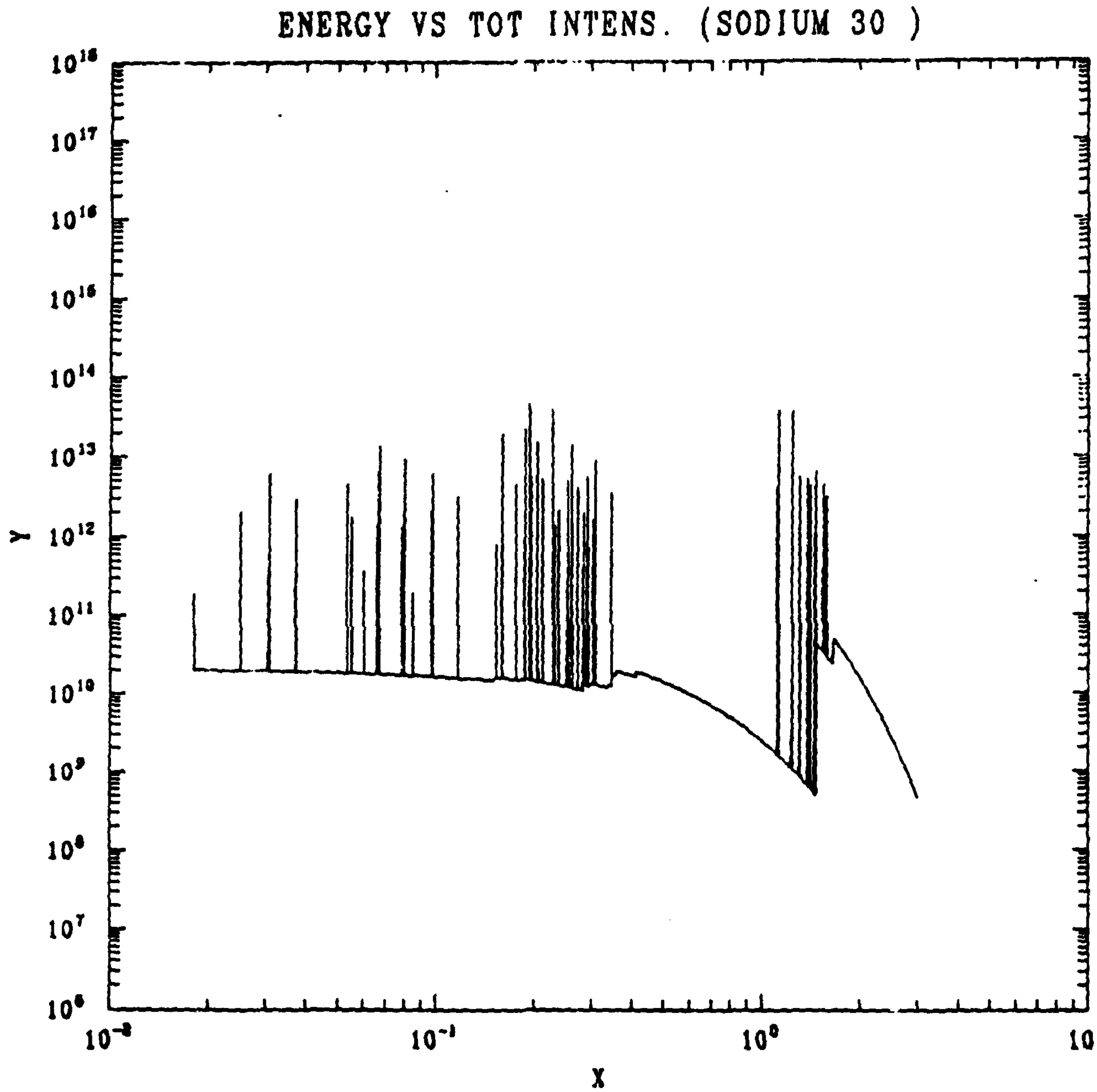

Fig. 8. Radiated emission spectrum as a function of energy.

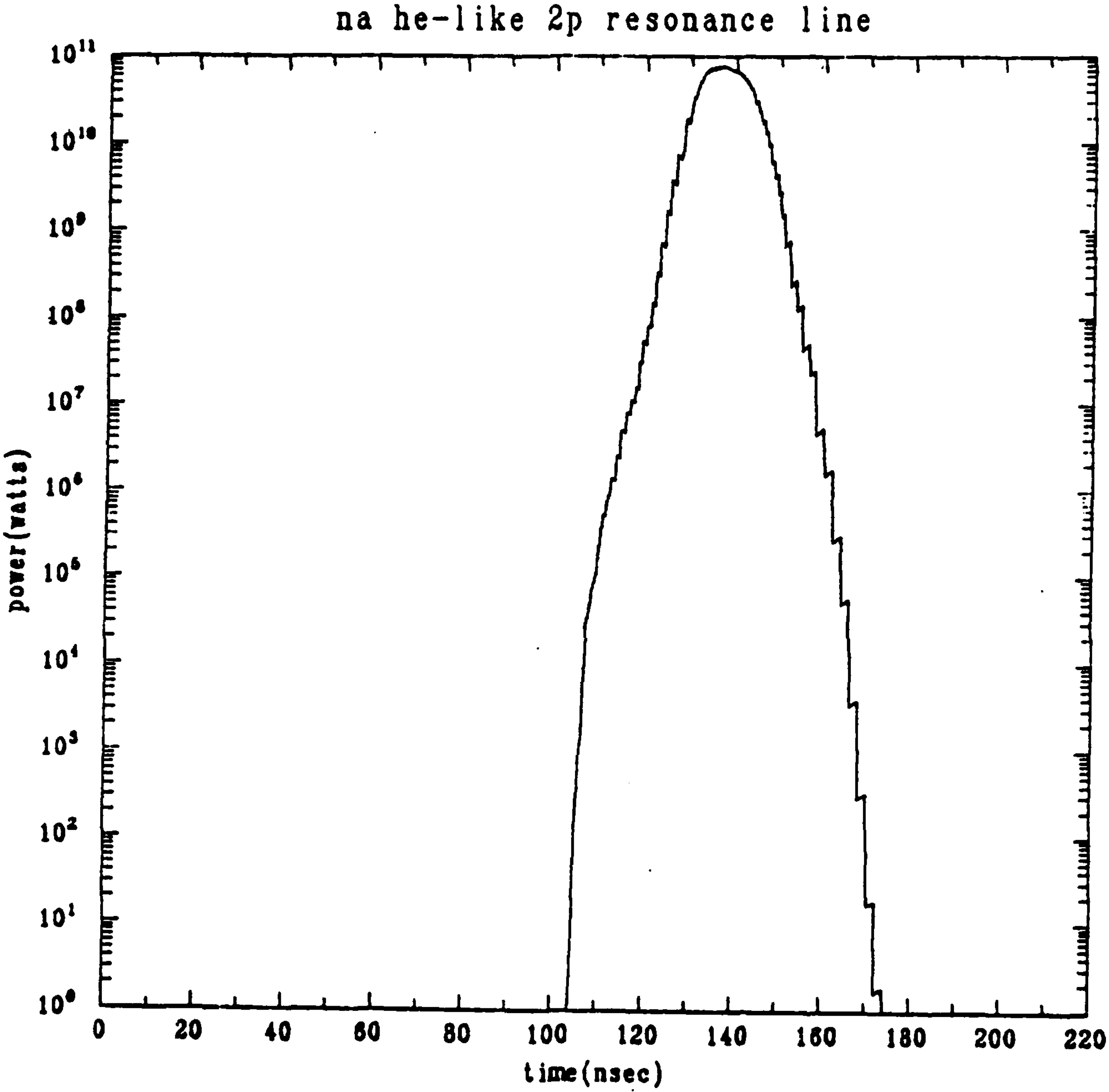

Fig. 9. Power radiated in heliumlike sodium resonance line as a function of time.

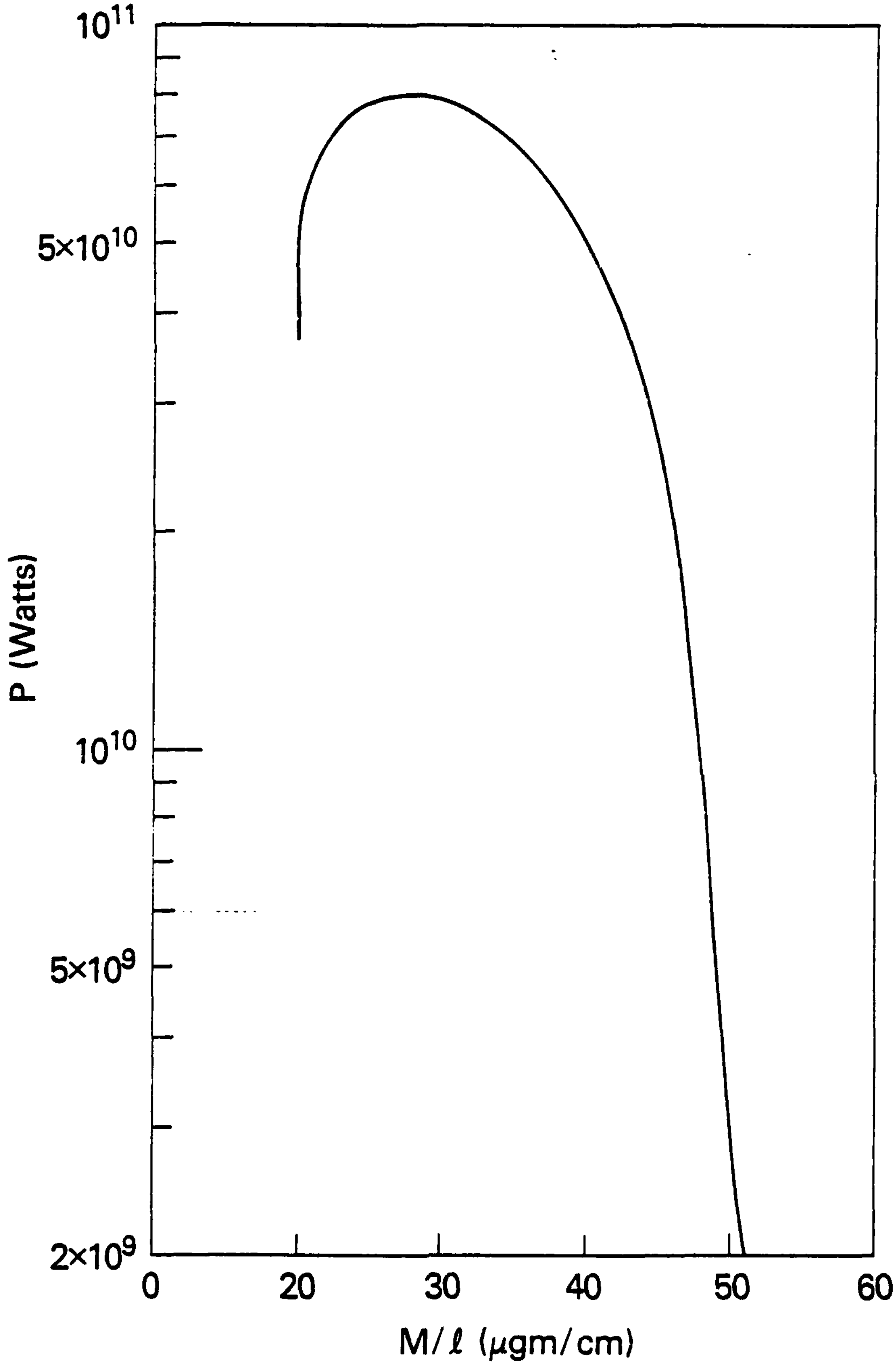

Fig. 10. Power radiated in heliumlike sodium resonance line as a function of M/ℓ for $\Delta R = 0.60$ cm.

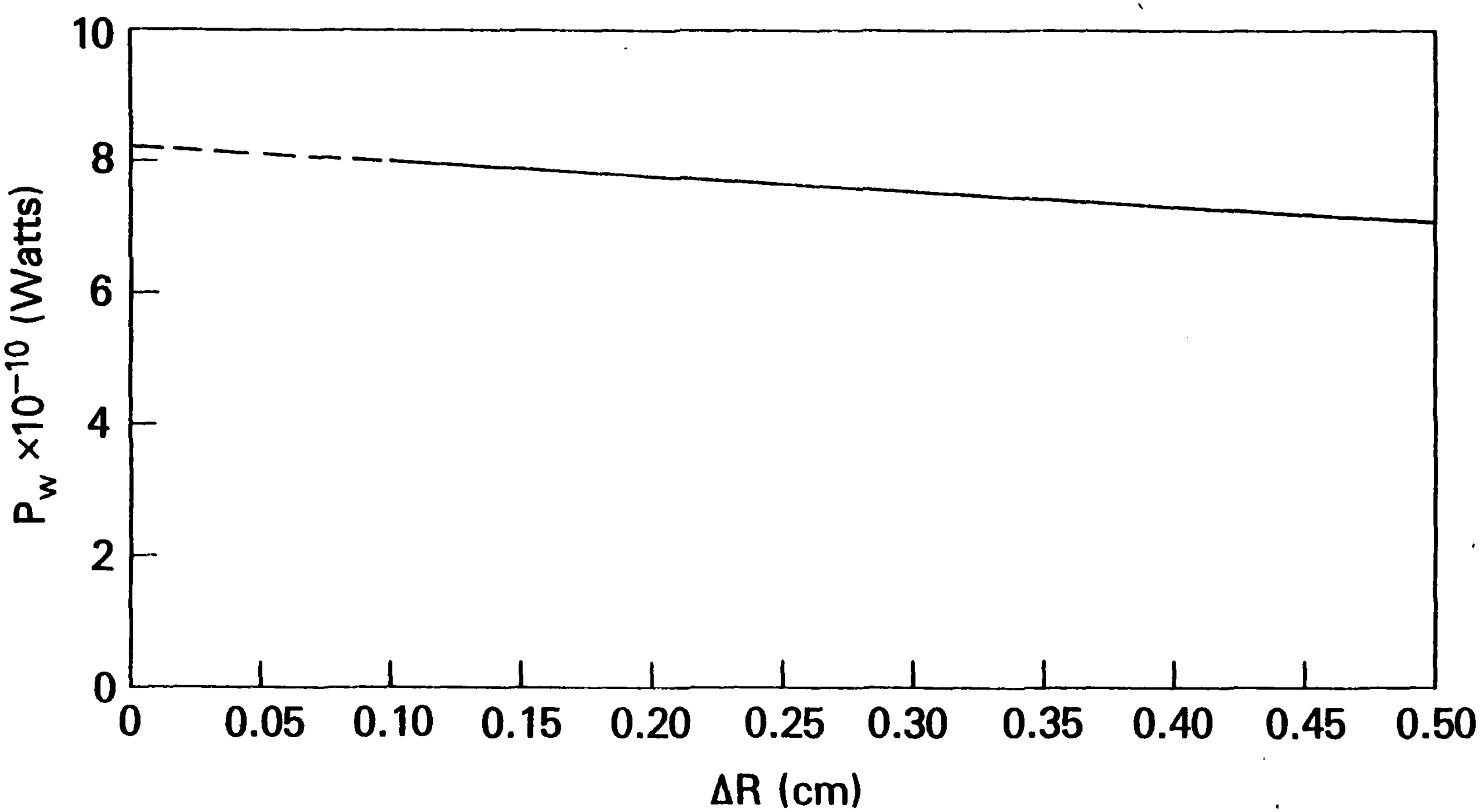

Fig. 11. Power radiated in heliumlike sodium resonance line as a function of ΔR for $M/\ell = 30\ \mu gm/cm$.

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